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Researchers generally agree that high aerobic fitness achieved through physical training will reduce the physiological strain to exercise in the heat, but does not replace the benefits of an exercise-heat acclimation program. In addition, high aerobic fitness is hypothesized as a major factor in the small decay and rapid re-acclimation of individuals after they ceased exercising in hot environments. However, recent work from our laboratory suggests that improved aerobic fitness by physical training must be associated with significant elevations in core temperature during the training process in order to improve

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exercise-heat tolerance. Thus, high levels of aerobic fitness, per se, can not always be associated with improved exercise-heat tolerance. Despite the disadvantages to heat transfer of being smaller and having larger skinfold thicknesses as compared to men, women do not appear to be at a comparative disadvantage during the performance of exercise in the heat. Two recent studies comparing men and women with similar aerobic fitness indicate no major physiological differences between genders in both humid and dry heat for cardiovascular and thermoregulatory responses to these environments either before or after acclimation. Our laboratory has reported that after exercise-heat acclimation under wet conditions (mild or hot), females tolerate the heat in a more efficient fashion than males while under hot-dry conditions males seem to be at some physiological advantage. Even fewer studies are reported which evaluate physiological differences in heat tolerance to exercise in relation to age. In general, exercise-heat tolerance is reduced in pre-pubertal children (boys and girls) and older adults (men and women) compared to young men and women. However, aerobically fit older adults seem to have far fewer decrements in the performance of exercise in the heat than less fit older adults.

FACTORS WHICH ALTER HUMAN PHYSIOLOGICAL RESPONSES DURING EXERCISE-HEAT ACCLIMATION

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ABSTRACT

Researchers generally agree that high aerobic fitness achieved through physical training will reduce the physiological strain to exercise in the heat, but does not replace the benefits of an exercise-heat acclimation program. In addition, high aerobic fitness is hypothesized as a major factor in the small decay and rapid re-acclimation of individuals after they ceased exercising in hot environments. However, recent work from our laboratory suggests that improved aerobic fitness by physical training must be associated with significant elevations in core temperature during the training process in order to improve exercise-heat tolerance. Thus, high levels of aerobic fitness, per se, can not always be associated with improved exercise-heat tolerance. Despite the disadvantages to heat transfer of being smaller and having larger skinfold thicknesses as compared to men, women do not appear to be at a comparative disadvantage during the performance of exercise in the heat. Two recent studies comparing men and women with similar aerobic fitness indicate no major physiological differences between genders in both humid and dry heat for cardiovascular and thermoregulatory responses to these environments either before or after acclimation. Our laboratory has reported that after exercise-heat acclimation under wet conditions (mild or hot), females tolerate the heat in a more efficient fashion than males while under hot-dry conditions males seem to be at some physiological advantage. Even fewer studies are reported which evaluate physiological differences in heat tolerance to exercise in relation to age. In general, exercise-heat tolerance is reduced in pre-pubertal children (boys and girls) and older adults (men and women) compared to young men and women. However, aerobically fit older adults seem to have far fewer decrements in the performance of exercise in the heat than less fit older adults.

I. INTRODUCTION

This article addresses three factors which are thought to alter human physiological responses during exercise-heat acclimation. These factors are (a) the influence of cardiorespiratory endurance training and aerobic fitness on the exercise-heat acclimation process, (b) the physiological comparison between genders during the performance of exercise in the heat, and (c) the physiological effects of aging on exercise-heat acclimation. Topics are discussed from a brief historical perspective followed by recent observations. All three of these factors should be of some interest to environmental and thermoregulatory physiologists, clinicians, and industrial and military scientists.

II. PHYSICAL TRAINING AND AEROBIC FITNESS

A. Historical Perspective

The importance of endurance training and/or aerobic fitness on the physiological adjustments to exercise in the heat and the process of heat acclimation has been a controversial subject for nearly two decades. However, two recent reviews (1,2) have evaluated this topic in detail from a historical perpective. Both reviews suggest possible methodological flaws in most of the early studies concerning this topic which makes them difficult to evaluate.

Improved aerobic fitness from physical training has been suggested to increase the sensitivity of the sweating response (peripheral effect) without changing the threshold temperature for this response (3). These same authors further suggested that exercise-heat acclimation lowered the threshold temperature without altering the sensitivity of the sweating response. Therefore, peripheral adaptations for heat dissipation appeared to be potentiated with improved aerobic fitness while central adaptations became involved during exercise-heat acclimation.

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INSERT FIGURE 1 ABOUT HERE

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Another debatable issue is whether maximal aerobic power ($\dot{V}O_{2\,max}$) is related to either improved exercise-heat tolerance or a more rapid rate of heat acclimation. As illustrated in Figure 1, two different authors (4,5) utilizing different climates (wet and dry) independently reported that an individual's $\dot{V}O_{2\,max}$ accounted for between 42-46% of the variability determining the core temperature after three hours of exercise in the heat (5), or the heat acclimation day for a plateau in core temperature (4). In contrast other authors (6,7) have reported insignificant relationships between $\dot{V}O_{2\,max}$ and either exercise endurance or final core temperature in the heat. However, most of the studies

which have shown a lack of relationship use relatively few subjects and/or homogeneously fit subjects.

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INSERT TABLE 1 ABOUT HERE

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Table 1 compares the percentage loss of heat acclimation during winter months observed by two different authors (4,8) for final rectal temperature (T_{re}) and heart rate (HR) responses. One author (8) showed significant losses for both physiological responses after the 1st, 2nd, and 3rd weeks in cool conditions with the entire acclimation gain for HR being lost by the 3rd week, and also nearly half of the T_{re} improvement being lost. The other author (4) showed non-significant losses for both responses at somewhat comparable time periods. While the earlier study (8) failed to quantify the aerobic fitness levels of their subjects, Pandolf et al. (4) hypothesized that the high aerobic fitness of their subjects was related to the small decay and rapid reinduction of acclimation.

B. Recent Observations

Recently, Avellini et al. (9) studied the effects of physical training on exercise-heat tolerance. Three groups (n=5, each) of male volunteers were matched initially for $\dot{V}O_{2\ max}$ and then physically trained on a cycle ergometer for one hour$\cdot$day^{-1}, five days$\cdot$week^{-1} at 75% of their individual $\dot{V}O_{2\ max}$ for four weeks. One group trained on land while the other two groups trained while immersed to the neck in water of either 20° or 32°C. After one hour of training, T_{re} rose about 1.1°C for land training, 0.6°C for the warm water (32°C) group but showed a steady decline in the cold water (20°C) group. After training, total body sweat rate averaged 600 $g \cdot m^{-2} \cdot h^{-1}$ for the land group, 200 $g \cdot m^{-2} \cdot h^{-1}$ for the warm water group with no measureable loss in cold water. After four weeks of training, the $\dot{V}O_{2\ max}$ increased significantly in all three groups. For the land training group, the $\dot{V}O_{2\ max}$ increased by 16% while the warm water group increased 13% and the cold water group increased 15%. There were no significant differences in $\dot{V}O_{2\ max}$ between groups after this month long training period.

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INSERT FIGURE 2 ABOUT HERE

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Figure 2 shows the mean values of final T_{re} and mean skin temperature ($\bar{T}_{sk}$) for each of the three groups for pre-training (HEAT STRESS 1), post-training (HEAT STRESS 2), and post-acclimation (HEAT STRESS 3). The post-training evaluation also served as the pre-acclimation session. All heat stress tests were identical three hour exposures at

49°C, 20% relative humidity while walking at about 30% $\dot{V}O_2$ max. Before physical training, no significant differences were observed between groups for T_{re}. After training, T_{re} decreased by about 0.5°C for the land and warm water groups but increased significantly for the cold water group. The cold water group differed significantly from the other two groups after training. After heat acclimation, final T_{re} was 38.1°, 38.3° and 38.4°C for the land, warm water and cold water groups, respectively. There were no significant differences between groups after acclimation; however, all groups displayed lower values compared to post-training (pre-acclimation). Similar trends can be seen for $\bar{T}_{sk}$ between groups for these same comparisons.

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INSERT FIGURE 3 ABOUT HERE

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As seen in Figure 3, final HR responses were expectedly similar between the three groups prior to training. Final HR decreased significantly in all three groups following physical training. However, the greatest decline was seen for land training (29 b·min^{-1}) while the warm water group decreased 14 b·min^{-1} and the cold water group decreased by 18 b·min^{-1} after training. Heat acclimation served to further significantly reduce final HR to similar levels in all three groups.

These findings suggest that improved aerobic fitness by physical training must be associated with significant elevations in core temperature during the training process in order to improve the thermoregulatory component of exercise-heat tolerance. However, the cardiovascular component to exercise-heat tolerance can be inhanced somewhat through these different training regimens. Therefore, high levels of aerobic fitness, per se, can not in all instances be associated with improved exercise-heat tolerance particularly from a thermoregulatory standpoint.

III. GENDER CONSIDERATIONS

A. Historical Observations

The responses of men to alterations in environmental temperature have provided the basis for our understanding of human exercise-heat tolerance and thermoregulation. There is less certainty about the thermoregulatory response patterns of women. Physiological reponses to exercise-heat stress may be different between genders due to several factors, including the lower cardiorespiratory fitness, the higher per cent body fat, the lower body weight, the lower skin surface area and the higher surface area-to-mass ratio (A_D·wt^{-1}) of women than men. In addition, hormonal fluctuations of estrogen and progesterone associated with the menstrual cycle may alter women's tolerance to exercise-heat stress.

Several investigators have shown that women thermoregulate less effectively than men when exposed to an acute heat stress (10,11,12). Under the same thermal load, deep body temperatures and heart rates were higher and sweating rates were lower in women (12,13,14). Although heat acclimation eliminates many of these gender-related physiological differences, sweating rate still remained lower for women (12,15). However, none of these studies matched the genders prior to evaluation in terms of $\dot{V}O_{2\ max}$, physical and/or any morphological considerations.

B. Recent Findings

Figure 4 depicts the findings of Avellini et al. (16) both before and after a 10-day heat acclimation program for four men and four women matched for aerobic power, surface area and $A_D \cdot wt^{-1}$ during an attempted three hour heat stress test in humid heat (T_{db} = 36°C, T_{wb} = 32°C) while walking at 1.56 $m \cdot s^{-1}$ (2% grade). Before acclimation, the final T_{re} for the men averaged 38.60°C while comparative values were lower at 38.04°C (pre-ovulatory) and 38.40°C (post-ovulatory) for the women. In addition, the HR responses for the men were consistently 13-25 $b \cdot min^{-1}$ higher than for the women throughout the pre-acclimation exposure. Although the men began the pre-acclimation exposure with a 1°C lower $\bar{T}_{sk}$, there were no differences between genders at other time comparisons.

After acclimation, the T_{re}, $\bar{T}_{sk}$ and HR responses between genders were similar at 90 min. However, at 180 min the T_{re} and HR responses were higher for the men compared to the women; however, $\bar{T}_{sk}$ did not differ between genders at this time point. A trend was noted for the men to have higher sweat rates particularly in the pre-acclimation state in this study. These authors (16) concluded that "when fitness levels are similar, the previously reported sex-related differences in response to an acute heat exposure seem to disappear except for the higher sweat rate for men."

INSERT FIGURE 4 AND TABLE 2 ABOUT HERE

Table 2 summarizes the pre- and post- acclimation observations of Frye and Kamon (17) who compared four men and four women matched for maximal aerobic power and $A_D \cdot wt^{-1}$ during an attempted three hour exposure at 30% $\dot{V}O_{2\ max}$ to dry heat (T_{db} = 48°C, T_{wb} = 25°C). Prior to acclimation, the women had slightly but not significantly higher final values for T_{re}, $\bar{T}_{sk}$ and HR. However, the final mean sweat rate ($\dot{M}_{sw}$) was significantly higher for the men. After acclimation, these same trends between genders were observed; however, differences in final $\dot{M}_{sw}$ between genders were not significant. These authors (17) "concluded that sex alone does not determine responses to heat stress. Consideration should also be given to the relative cadiovascular strain, state of acclimation, and the ambient conditions."

....

INSERT TABLE 3 ABOUT HERE

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Gender related trends in thermoregulatory responses to a variety of climates are summarized in Table 3 (18). In comfortable climatic conditions (20°C, 40% RH), men and women have similar physiological responses. Under wet conditions (mild or hot), women appeared to tolerate the heat slightly better than men. The women displayed lower deep body and skin temperatures, and therefore had less heat storage (ΔS), while showing reduced sweating rates and subsequently less dehydration than men. In contrast, under hot-dry conditions, the men appeared to be at a slight physiological advantage. Compared to the women, they had lower T_{re}, $\bar{T}_{sk}$, HR and ΔS, but similar sweating rates. A possible explanation for these differences could involve three considerations. The higher $A_D \cdot wt^{-1}$ for women may be a morphological advantage in hot-wet climates, and a disadvantage in hot-dry climates. Women seemed to have better peripheral feedback from skin wettedness which suppressed nonefficient sweating in humid environments. Women also appeared to have a higher central thermoregulatory set point than men, and therefore were more intolerant of hot-dry environments. However, significant differences were generally not found between the genders in subsequent experimentation for HR, core temperature and sweat loss during additional hot-wet and hot-dry experiments (19).

It was further concluded from the earlier experiments by our laboratory that prolonged exposure (four hour) did not enhance any gender-related physiological differences in response to dry heat (20). Women seemed to be able to maintain sufficiently high sweating rates over four hours to reach and maintain thermoequilibrium. Additionally, it was found that both genders acclimated to a hot-dry environment at the same rate (21).

Most recently, our laboratory has studied the gender related physiological responses during exercise in three environmental conditions (comfortable, hot-dry and hot-wet) when 5% hypohydrated (19). In general, significant differences were not found between the genders for final exercise T_{re}, $\bar{T}_{sk}$ or HR in these conditions when either eu-or hypohydrated. We also found that cell volume and vascular fluid shifts were not different between genders when either eu- or hypohydrated in a hot-dry environment (22). The present data indicated that physiological differences between genders were not systematically altered by level of hydration. In conclusion, when genders are similar with regard to aerobic fitness level, $A_D \cdot wt^{-1}$ and percent body fat, they do not differ dramatically in exercise-heat tolerance, thermal strain, and rate of heat acclimation; these reactions are not altered between genders when hypohydrated.

IV. EFFECTS OF AGING

Few studies have reported the effect of age on the physiological responses to exercise-heat stress. As shown in Figure 5, Wagner et al. (23) compared preadolescent boys (11-14 years) to young men (25-30 years) before and after heat acclimation (eight consecutive days) while walking (1.56 $m \cdot s^{-1}$) in dry heat (T_{db} = 49°C, T_{wb} = 26.6°C). Both before and after acclimation, these boys displayed higher T_{re}, $\bar{T}_{sk}$ and HR responses, and lower evaporative cooling than the young men. Postadolescent boys (15-16 years) displayed better temperature regulation than preadolescent boys but did not perform as well as these same young men both pre- and post-acclimation (23). Similar trends in thermoregulatory responses were reported by Drinkwater and Horvath (24) but for young girls. These authors concluded that preadolescent children (boys and girls) appeared more exercise-heat intolerant due to (a) the instability of an immature cardiovascular system (24) and/or (b) a limited sweating capability (23).

INSERT FIGURES 5 AND 6 ABOUT HERE

In general, exercise-heat tolerance is believed to be reduced in older adults (23,24). Older men (46-47 years) have been shown to have higher T_{re}, $\bar{T}_{sk}$ and HR responses, and lower evaporation rates than younger men (20-29 years) during exercise (walking, 1.56 $m \cdot s^{-1}$) in the heat (T_{db} = 49°C, T_{wb} = 26.6°C) both pre- and post-acclimation (23) as illustrated in Figure 6. Thus, these older men showed the same trends in these selected physiological responses when compared to the younger men as did the younger boys both pre- and post-acclimation (23). These same patterns of reduced exercise-heat tolerance were reported by Drinkwater and Horvath (24) but for older women. It has also been reported that older adults started to sweat later and sweat less during exercise in the heat than younger adults (25,26). Some authors have concluded that older individuals are more exercise-heat intolerant because of a limited sensitivity and secretory capacity of their sweating response (23), and/or the decrease in cardiovascular fitness common to most older individuals (24).

INSERT FIGURE 7 ABOUT HERE

The acclimation responses to exercising (walking, 1.56 $m \cdot s^{-1}$ at 4-5.6% grade) in the heat (T_{db} = 40°C, T_{wb} = 23.5°C) of men during 1942 and these same individuals 21 years later have been reported (27). By some of the usual physiological criteria (T_{re}, $\bar{T}_{sk}$ and HR), these older men acclimated to exercise in the heat in the same manner, and to the same extent as when they were younger. However, the initial cardiovascular strain

seen prior to acclimation was greater for the older men in terms of relative cardiac cost given what is known about the reduction in maximum HR with increasing age. Nevertheless, these older men exhibited about the same degree of overall strain during exercise in the heat as they did 21 years earlier, and acclimated about as well (27); however, these individuals may not be "typical" old men because of their habitually active lifestyles. More definitive research is needed to advance our understanding of exercise in the heat and its interaction with aging. In closing, we would hypothesize that if older and younger men were matched for maximal aerobic power and surface area to mass ratio, many of the reported differences in heat tolerance to exercise with aging would disappear.

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FIGURE LEGENDS

Figure 1. Maximal oxygen uptake ($ml \cdot kg^{-1} \cdot min^{-1}$) in relation to either the final rectal temperature in hot environments or the acclimatization day for a plateau in rectal temperature (Source: reference 2).

Figure 2. Final rectal and mean skin temperatures for the land, warm-water, and cold water training groups as evaluated before physical training (HEAT STRESS 1), after physical training (HEAT STRESS 2), and after heat acclimation (HEAT STRESS 3)(Source: reference 9).

Figure 3. Final heart rate responses for the same three physical training groups and same periodic evaluations as in Fig. 2. (Source: reference 9).

Figure 4. Rectal temperature, heart rate and mean skin temperature over time comparing men and women both pre- and post- acclimation. Men and women were matched for maximal aerobic power, surface area, and surface area to mass ratio (Redrawn for reference 16).

Figure 5. Rectal temperature, mean skin temperature, heart rate and sweat evaporative rate over time comparing preadolescent boys and young men both pre- and post-acclimation (Redrawn from reference 23).

Figure 6. Rectal temperature, mean skin temperature, heart rate and sweat evaporative rate over time comparing younger and older men both pre- and post-acclimation (Redrawn from reference 23).

Figure 7. Rectal temperature, mean skin temperature and heart rate responses of four men evaluated over eight days of acclimation to heat in 1942 and these same men evaluated in 1963 (Redrawn from reference 27).

TABLE 1. PERCENTAGE LOSS OF ACCLIMATION IN WINTER

WEEKS	1ST	2ND	3RD
RECTAL TEMPERATURE			
WILLIAMS ET AL. (8)	26%	35%	45%
PANDOLF ET AL. (4)	13% *	18% *	4% *
	(SIX DAYS)	(TWELVE DAYS)	(EIGHTEEN DAYS)
HEART RATE			
WILLIAMS ET AL. (8)	65%	87%	92%
PANDOLF ET AL. (4)	23% *	20% *	29% *
	(SIX DAYS)	(TWELVE DAYS)	EIGHTEEN DAYS)

* NOT SIGNIFICANTLY DIFFERENT FROM LAST (9TH) DAY OF ACCLIMATION.
(FROM PANDOLF, MED. SCI. SPORTS 1979)

TABLE 2. FINAL VALUES FOR RECTAL TEMPERATURE, MEAN SKIN TEMPERATURE, HEART RATE, AND MEAN SWEAT RATE FOR MEN AND WOMEN BOTH PRE - AND POST-ACCLIMATION TO DRY HEAT.

STATE OF ACCLIMATION	SEX	VARIABLE T_{RE} (°C)	$\bar{T}_{SK}$ (°C)	HR ($B \cdot MIN^{-1}$)	MEAN $\dot{M}_{SW}$ ($W \cdot M^{-2}$)
PRE-ACCLIMATION	WOMEN	39.01±0.19	38.37±0.71	141.6±9.6	289.6±47.8
	MEN	38.57±0.40	37.90±0.43	129.9±12.1	390.4±7.8
	LEVEL OF SIGNIFICANCE	NS	NS	NS	$P < 0.05$
POST-ACCLIMATION	WOMEN	38.12±0.13	37.15*±0.40	120.6*±10.5	407.8 ±24.2
	MEN	37.96±0.23	36.71*±0.28	106.3*±9.5	430.2*±29.7
	LEVEL OF SIGNIFICANCE	NS	NS	NS	NS

VALUES ARE MEANS ± SD. ASTERISK INDICATES A SIGNIFICANT ($P < 0.05$) CHANGE FROM PRE- TO POST-ACCLIMATION.

(FROM FRYE AND KAMON, J. APPL. PHYSIOL. 1981)

TABLE 3. SUMMARY OF GENDER-RELATED TRENDS IN THERMOREGULATORY RESPONSES TO VARIOUS CLIMATES

	COMFORT	MILD-WET	HOT-WET	HOT-DRY
T_{re}	=	-	-	+
HR	=	=	=	+
$\bar{T}_{sk}$	=	-	-	+
ΔS	=	-	-	= or +
$\dot{M}_{sw}$	=	-	-	=
DEHYDRATION	=	=	-	=
H_2O CONSUMPTION	=	=	+	+

= NO DIFFERENCE

- FEMALES ARE LOWER THAN MALES

+ FEMALES ARE HIGHER THAN MALES

(FROM SHAPIRO, ET AL., J. APPL. PHYSIOL. 1980)

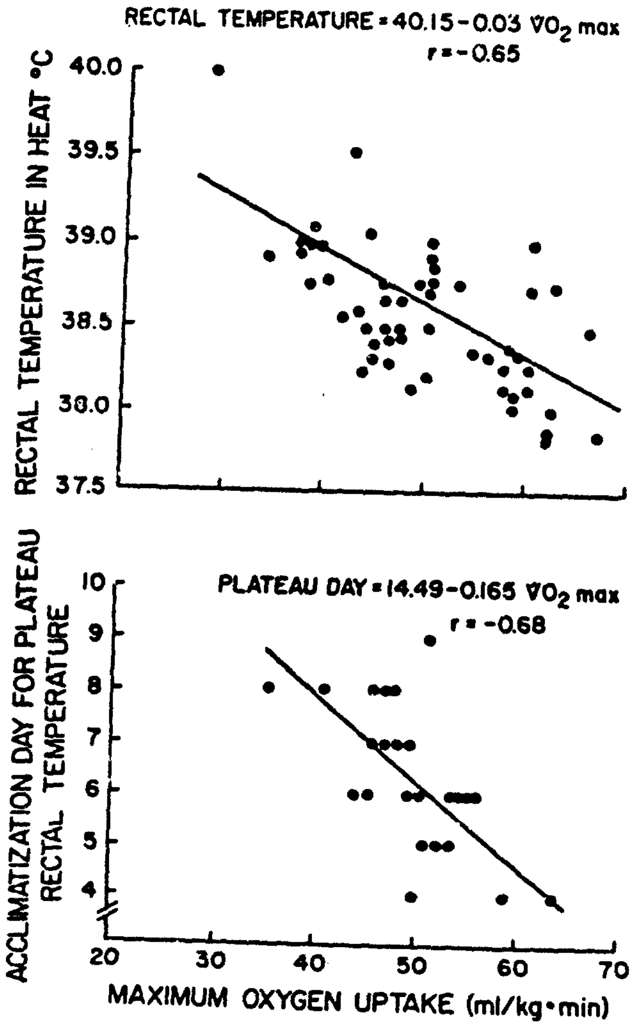

RECTAL TEMPERATURE = 40.15 - 0.03 VO2 max
r = -0.65
RECTAL TEMPERATURE IN HEAT °C
40.0
39.5
39.0
38.5
38.0
37.5
PLATEAU DAY = 14.49 - 0.165 VO2 max
r = -0.68
ACCLIMATIZATION DAY FOR PLATEAU RECTAL TEMPERATURE
10
9
8
7
6
5
4
20
30
40
50
60
70
MAXIMUM OXYGEN UPTAKE (ml/kg•min)

FIG. 1

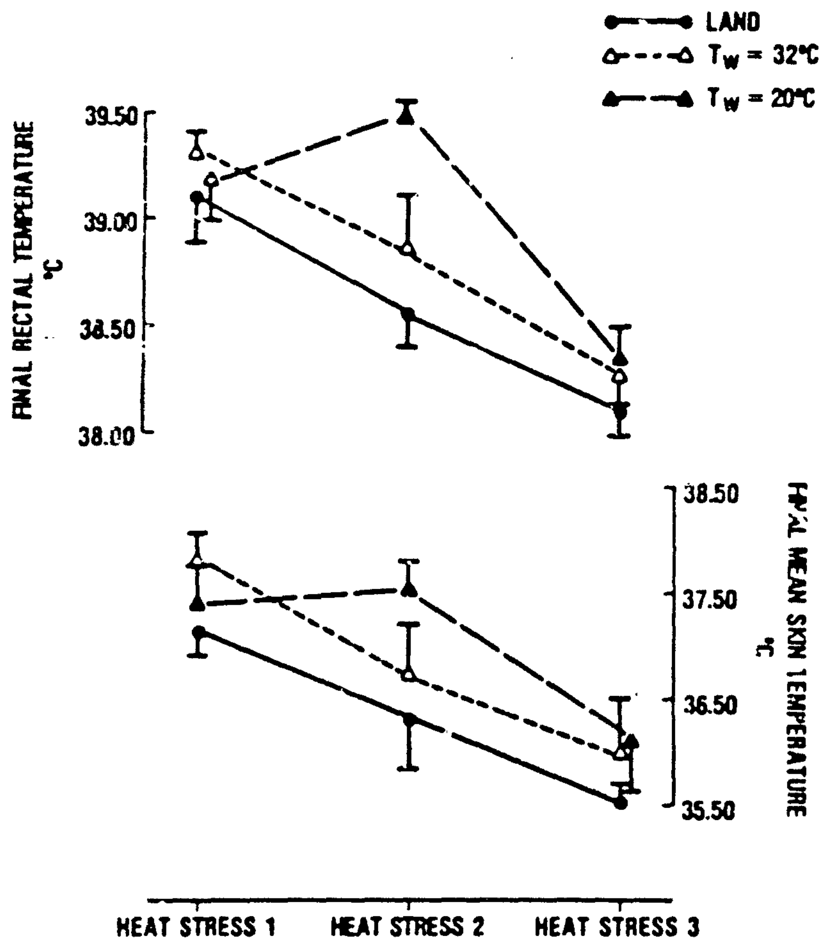

LAND
T_W = 32°C
T_W = 20°C
FINAL RECTAL TEMPERATURE °C
39.50
39.00
38.50
38.00
FINAL MEAN SKIN TEMPERATURE °C
38.50
37.50
36.50
35.50
HEAT STRESS 1
HEAT STRESS 2
HEAT STRESS 3

FIG. 2

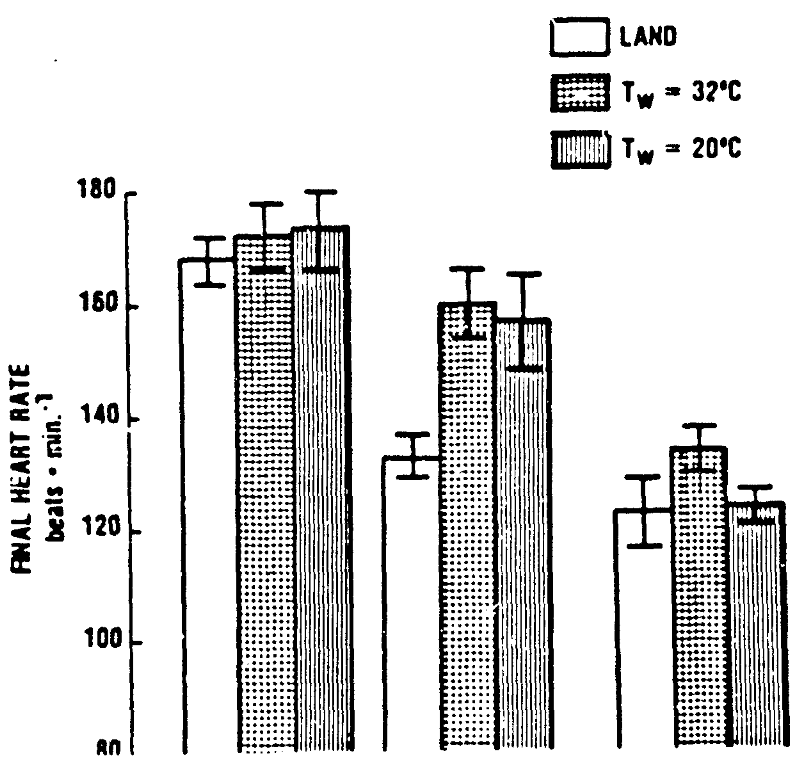
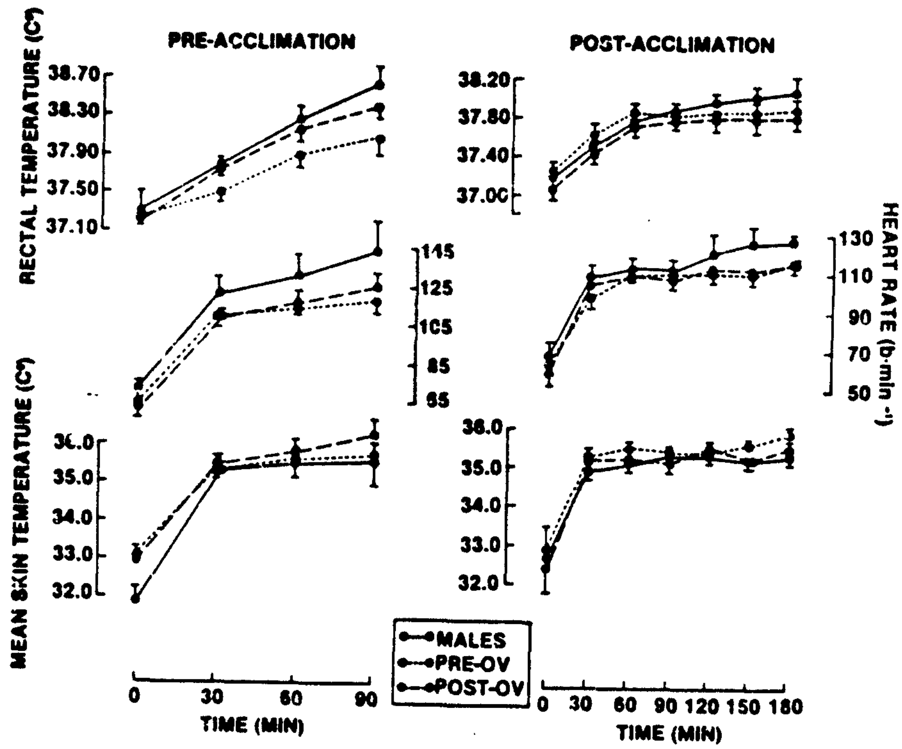
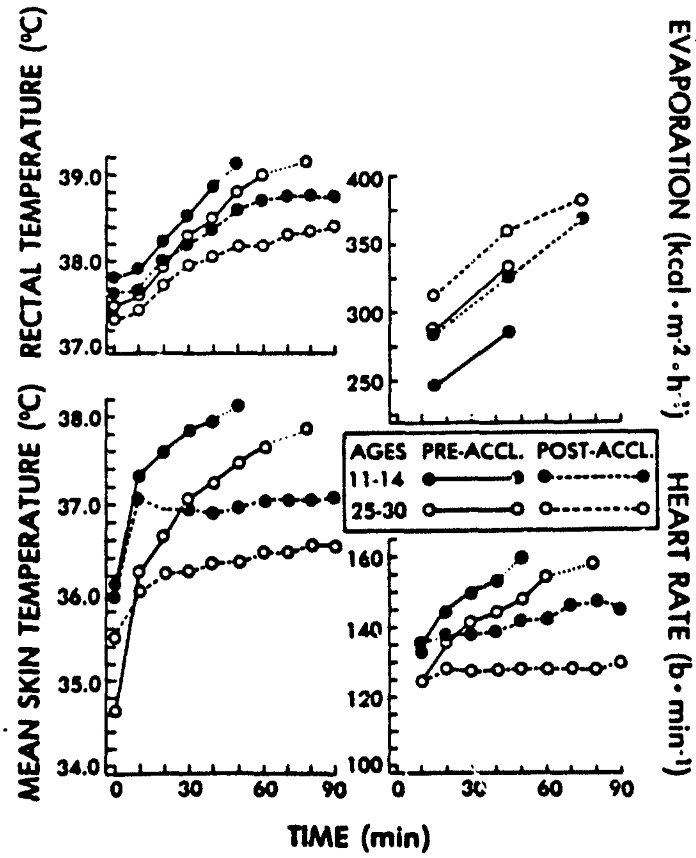

LAND
T_W = 32°C
T_W = 20°C
FINAL HEART RATE beats • min.$^{-1}$
180
160
140
120
100
80

FIG. 3



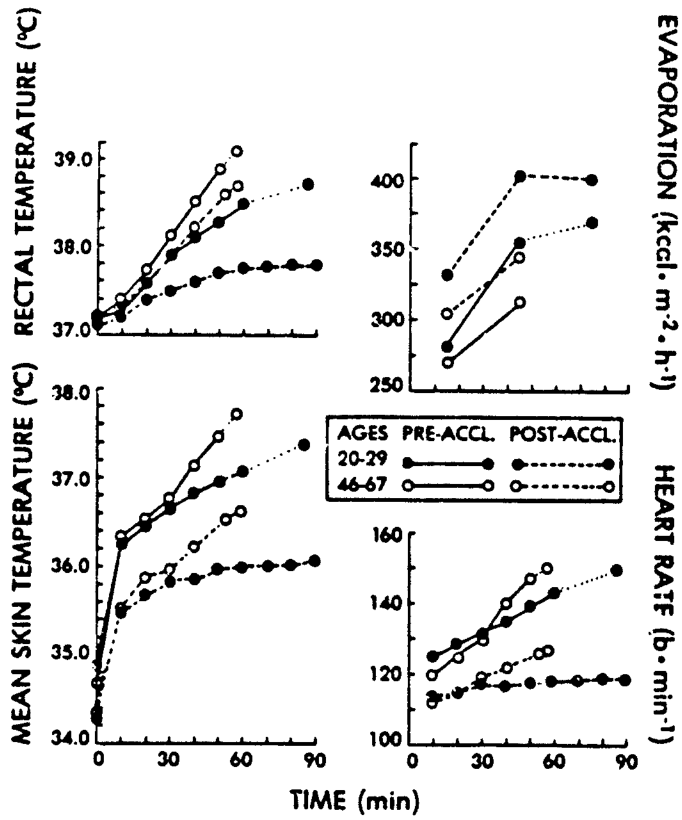
(FROM AVELLINI, ET. AL., J. APPL. PHYSIOL. 1980)

FIG.4



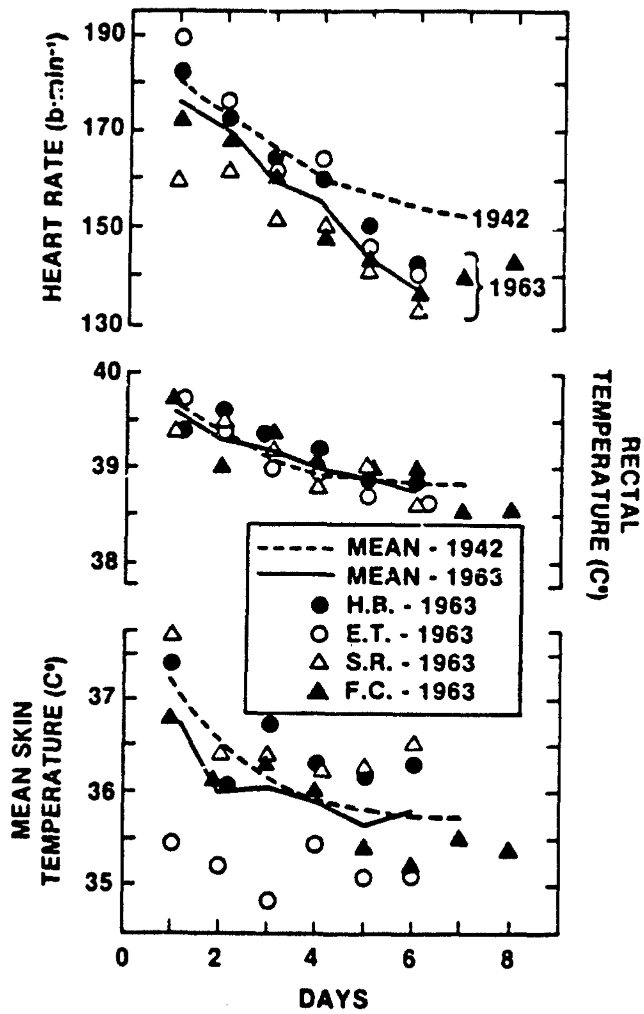
(From Wagner, et al., J. Appl. Physiol. 1972)

FIG.5



(From Wagner, et al., J. Appl. Physiol. 1972)

FIG.6



(FROM ROBINSON, ET. AL., J. APPL. PHYSIOL. 1965)

FIG. 7